A Very Large, Spontaneous Stratospheric Sudden Warming in a Simple AGCM: A Prototype for the Southern-Hemisphere Warming of 2002?

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Abstract

An exceptionally strong stratospheric sudden warming (SSW) that spontaneously occurs in a very simple stratosphere-troposphere AGCM is discussed. The model is a dry, hydrostatic, primitive-equation model without planetary stationary waves. Transient baroclinic wave-wave interaction in the troposphere thus provides the only source of upward propagating wave activity into the stratosphere. The model's SSW is grossly similar to the Southern-Hemisphere major SSW of 2002: it occurs after weaker warmings "precondition" the polar vortex for breaking, it involves a split of the polar vortex, and it has a downward-propagating signature. These similarities suggest that the Southern-Hemisphere SSW of 2002 might itself have been caused by transient baroclinic wave-wave interaction. Our simple model also provides some insight into how often such extreme events might occur. The frequency distribution of SSWs in the model have exponential, as opposed to Gaussian, tails. This suggests that very large-amplitude SSWs, though rare, might occur with higher frequency than might be naively expected.

1 Introduction

The austral winter of 2002 was exceptional in the Southern Hemisphere stratosphere because of the major stratospheric sudden warming (SSW) that occured in September — the only such warming ever observed there — and because of the very warm stratospheric temperatures that occured in the months leading up to the SSW (Baldwin et al. 2003; Newman and Nash 2003). It is unclear what might have brought about such an exceptional season. Baldwin et al. (2003) argue that extreme events of this kind can occur randomly over a sufficiently long period. Newman and Nash (2003) propose a more specific mechanism that involves an initial tropical wave event. One avenue to understanding the Southern-Hemisphere SSW of 2002 is to work within the simplest possible modeling framework that still captures the essential dynamical features of the coupled extratropical stratosphere-troposphere system. With this idea in mind, we demonstrate here that a very simple model of this system (Polvani and Kushner 2002; Kushner and Polvani 2003) is capable of producing a SSW that shares many parallels with the Southern-Hemisphere SSW of 2002, notably, its large amplitude.

2 Model

As we have described in detail in previous studies (Polvani and Kushner 2002; Kushner and Polvani 2003), our model solves the dry, hydrostatic, primitive equations on the sphere, with spectral T42 resolution in the horizontal, 40 levels in the vertical, and a flat lower boundary. The model's winds are linearly damped in a planetary boundary layer and in a sponge above 0.5 mb. The model's temperature field is relaxed towards a zonally symmetric and time independent equilibrium-temperature field, $T_{\rm eq}$. In the troposphere, $T_{\rm eq}$ closely follows the Held and Suarez (1994) prescription; in the stratosphere, $T_{\rm eq}$ transitions from winter polar-night conditions in the winter (Southern) hemisphere to standard atmosphere conditions in the summer (Northern) hemisphere. The model's circulation has an active baroclinic-eddy-driven jet in the troposphere, a tropical overturning circulation, and a stratospheric polar vortex in the winter hemisphere. The strength of the model's polar vortex is controlled by a parameter, γ, that is proportional to the strength of the pole-to-equator gradient in the stratospheric $T_{\rm eq}$. We here consider the "$\gamma = 2$" case of Polvani and Kushner (2002) and Kushner and Polvani (2003). The model is integrated for 12,000 days, and the last 11,000 days are used for analysis.

Because its lower boundary is flat, and because $T_{\rm eq}$ is zonally symmetric, our model has no stationary planetary waves. Thus, the model's stratospheric variability is driven by transient baroclinic wave-wave interaction alone, as described by Scinocca and Haynes (1997). Our model is simpler than the dry AGCM simulations of Taguchi and Yoden (2002a,b), which include topographic forcing in addition to baroclinic-eddy forcing. Another simplification compared to the Taguchi-Yoden simulations is that, because T_{eq} is time invariant, our model includes no seasonal cycle. Therefore, our model represents a very simple starting point for understanding the coupled stratosphere-troposphere dynamics underlying SSWs.

3 Results

Fig. 1 shows the time series, over the 11,000-day analysis period, of the temperature averaged meridionally over a polar cap extending from 90S to 60S at the 50mb level in the lower stratosphere. The mean value of this quantity is approximately 213K and there are many periods when the mean temperature exceeds 216K. But we note that there is one event, marked in the figure by an arrow as occuring at day 7121, in which the mean temperature exceeds 220K. The day-7121 event stands out as a departure of over 6 standard deviations from the time mean. This is illustrated by the right-hand axis in the figure that rescales the data in units of standard deviations from the time mean. That is, the right-hand axis represents the temperature as a nondimensional temperature anomaly

$$s(T) = \frac{\left(T - \overline{T}\right)}{\mathrm{std}(T)}, \tag{1}$$

where T is the meridionally averaged temperature, $\overline{T}$ is the time mean of the time series and $\mathrm{std}(T)$ is the temporal standard deviation of the time series.

[Figure 1 about here.]

The day-7121 warm anomaly at 50mb is a signature of a "major" SSW (as defined by Andrews et al. 1987, p.259). Fig. 2 shows snapshots of the zonal-mean temperature over six-day intervals starting at day 7115. From day 7115 to day 7121, high-latitude temperatures increase markedly throughout the stratosphere. For example, the polar temperature at 22 mb changes from 204K to 235K over this six-day interval. Since low-latitude temperatures do not change as much over the period, the sign of the meridional temperature gradient changes from positive to negative throughout the extratropical stratosphere. Stratospheric temperatures remain warm and the stratospheric temperature gradient remains negative or weakly positive until day 7133. The zonal-mean wind evolution (Fig. 3), as expected, follows closely the temperature evolution. Winds switch sign from westerly to easterly from day 7115 to 7121, and then back to weak westerly over the next 12 days.

[Figure 2 about here.]

[Figure 3 about here.]

Fig. 4 shows four snapshots of the potential vorticity on the 750K potential-temperature surface, starting at day 7107, instead of day 7115, to show the less disturbed state of the polar vortex before the warming. At day 7113, the polar vortex is elongated in a manner similar to that seen a few days before typical SSWs, including the Southern-Hemisphere SSW of 2002 (Baldwin et al. 2003) . The vortex is pinched at its center by day 7119 and is split by day 7125. This is the only occurrence of a split polar vortex in the entire integration. The complete breakup of the polar vortex is what makes this event qualitatively quite similar to the Southern-Hemisphere SSW of 2002, as seen by comparing Fig. 4 to Baldwin et al. (2003), Fig. 2.

[Figure 4 about here.]

Furthermore, similarly to the Southern-Hemisphere SSW of 2002 (see Newman and Nash 2003, Fig. 3), the day-7121 SSW in our model is preceded by a series of strong upward EP flux pulses from below that warm the stratosphere and weaken the polar vortex. To show this, we plot the 90S-60S meridionally averaged temperature anomaly (Fig. 5a), the 90S-40S meridionally averaged vertical EP-flux anomaly at 100 mb (Fig. 5b), and the 90S-40S meridionally averaged zonal-wind anomaly (Fig. 5c). All quantities are plotted as non-dimensional anomalies similar to eqn. (1), i.e. as $s(\cdot) = \left[(\cdot) - \overline{(\cdot)}\right]/\mathrm{std}(\cdot)$. The day-7121 SSW occurs after the stratosphere has been mildly warm for 200 days. This warm period is sustained by strong upward pulses of EP wave activity — several of these events are marked with yellow lines in each of the panels of the figure. The day-7121 SSW has an interesting precursor: at around day 7080, a particularly strong (4 standard deviation) pulse of wave activity brings about an 8 standard-deviation warming in the upper stratosphere whose impacts on the winds are confined to above 20mb. In this event, the polar vortex is greatly deformed, but does not split (not shown). This appears to precondition the vortex so that the somewhat weaker wave-activity pulse just before the day-7121 event can produce the major warming.

As is common in major warmings in the Northern Hemisphere, the Southern-Hemisphere SSW of 2002 exhibited downward propagation (Newman and Nash 2003). Similarly, after the day-7121 SSW in our model, Fig. 5a shows that anomalously warm temperatures descend into the troposphere, at least to 200 mb, and perhaps all the way to the surface, by day 7250.[1] The easterly anomaly in the winds, over the wider region 90S-40S (panel c)), descends but does not penetrate into the troposphere. Fig. 3 of Newman and Nash (2003) also shows, similarly to this figure, that the temperature signature of the observed SSW descends more

[1]The statistical significance of the signal in the lower troposphere is difficult to assess. By day 7200, the lower troposphere has been anomalously cool for several hundred days, and may be about to become anomalously warm, independently of what is happening in the stratosphere.

deeply into the troposphere than the zonal-wind signature.

Notice also, similarly to Fig. 3a of Newman and Nash (2003), that after the day 7121 warming, a cold-temperature anomaly descends from 1mb to 20mb as the warm-temperature anomaly descends below it. In Fig. 5c, we see a descending strong-wind anomaly above the descending weak-wind anomaly. These descending patterns suggest that a QBO-like wave-mean-flow interaction is occuring, along the lines proposed by Plumb and Semeniuk (2003) to explain downward-propagating stratosphere-to-troposphere signals in the Northern Hemisphere (Baldwin and Dunkerton 1999, 2001). The picture is that the breaking level of planetary wave activity absorption is being eroded downwards, resulting in a descending region above the breaking level which is being shielded from upward propagating wave activity.

[Figure 5 about here.]

The six-to-eight standard deviation major warming seen here is extreme but is, perhaps, not surprising, given the population of warm events that occur during the integration. In this model, as in other models and in the observations, stratospheric temperature variability is skewed and exponentially distributed (Taguchi and Yoden 2002a,b). Fig. 6 plots the histogram of the $s(T)$ time series in Fig. 1 with a logarithmic scale on the vertical axis. The warm events are exponentially distributed, as shown by a fit of an exponential function to the data for $s(T) \geq 0$ (see caption for details). The day-7121 SSW is located at the extreme right tail of the distribution and appears as a reasonable end point for the distribution rather than as an unexpected extreme value.

[Figure 6 about here.]

4 Conclusion

We have demonstrated that a very simple model of the Southern Hemisphere stratosphere that is forced only by tropospheric baroclinic eddies can give rise, spontaneously, to a SSW that is similar, in many important ways, to the observed Southern-Hemisphere SSW of September 2002. We agree with Baldwin et al. (2003) that, given the skewed distribution of warming temperatures in the observations, in this model, and in other models (Taguchi and Yoden 2002a,b), it is likely that extreme events like this one will occur over sufficiently long time periods as a result of random fluctuations in the coupled stratosphere-troposphere system. Therefore, there may be no need to invoke more complicated models to explain the 2002 event.

In closing, we point out that our model's day-7121 SSW was not the result of an attempt on our part to deliberately *simulate* the 2002 event. Instead, our model's extreme SSW occured spontaneously, and the main reason to document it is that it resembles so closely, albeit fortuitously, the 2002 event.

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List of Figures

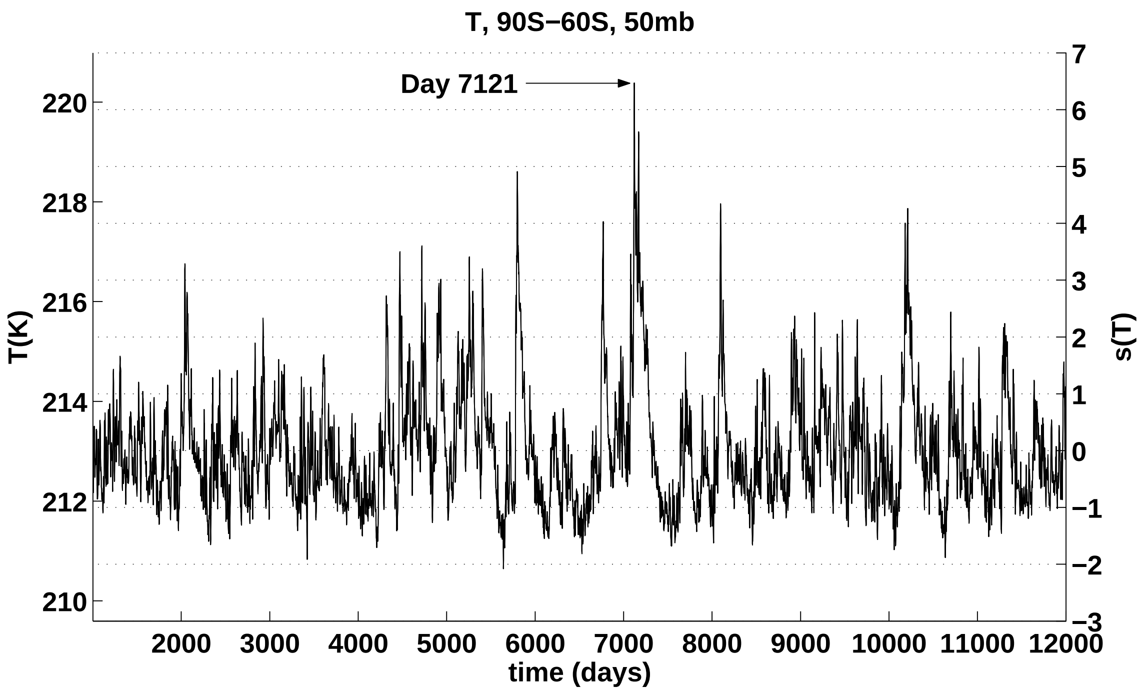

Figure 1: Time series of 50mb temperature averaged from 90S to 60S in Kelvin (left-hand axis) and in nondimensional anomaly units defined by (1) (right-hand axis). The day-7121 event is marked with an arrow.

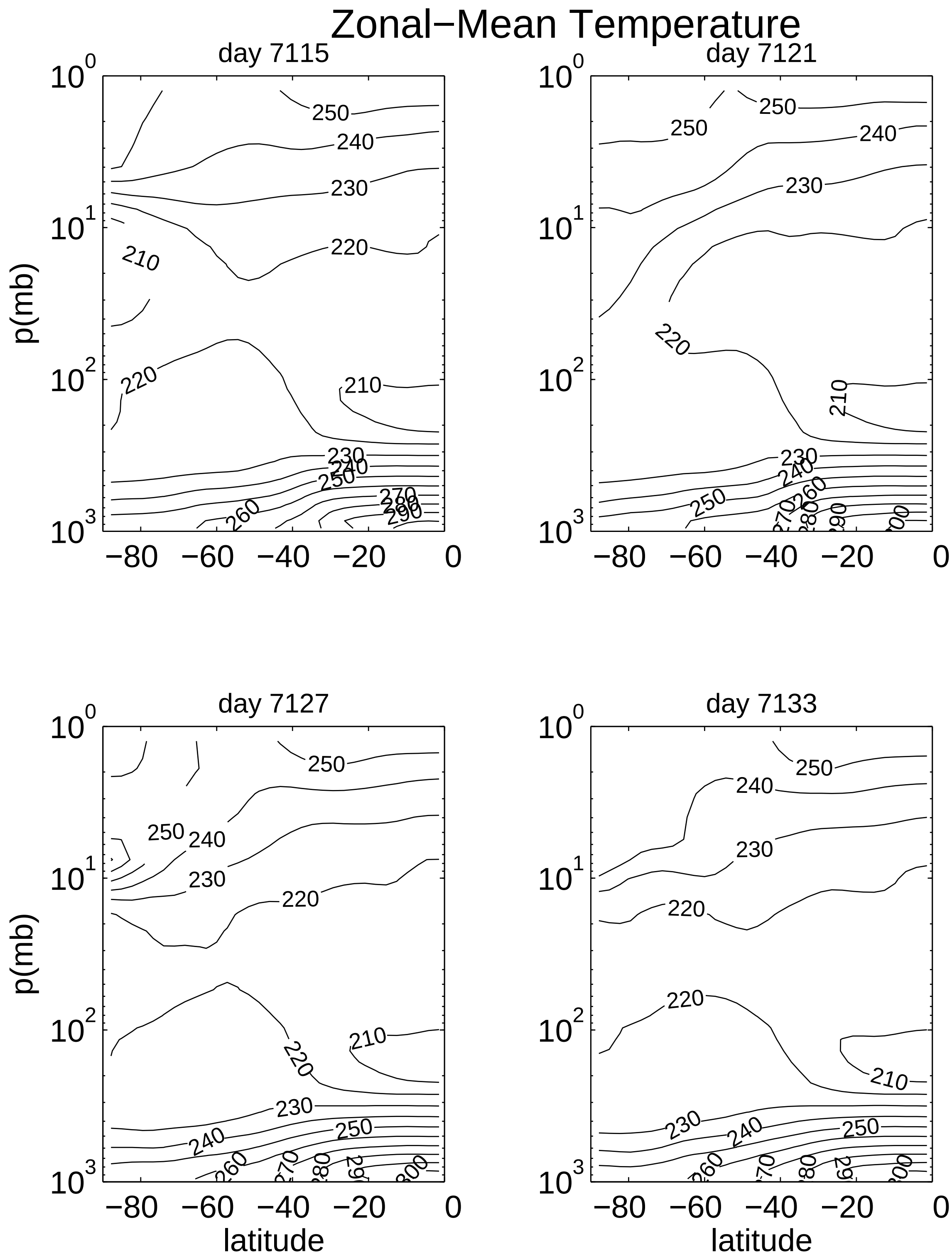

Figure 2: Southern-Hemisphere zonal-mean temperature for four days around the time of the day-7121 SSW. The contour interval is 10K.

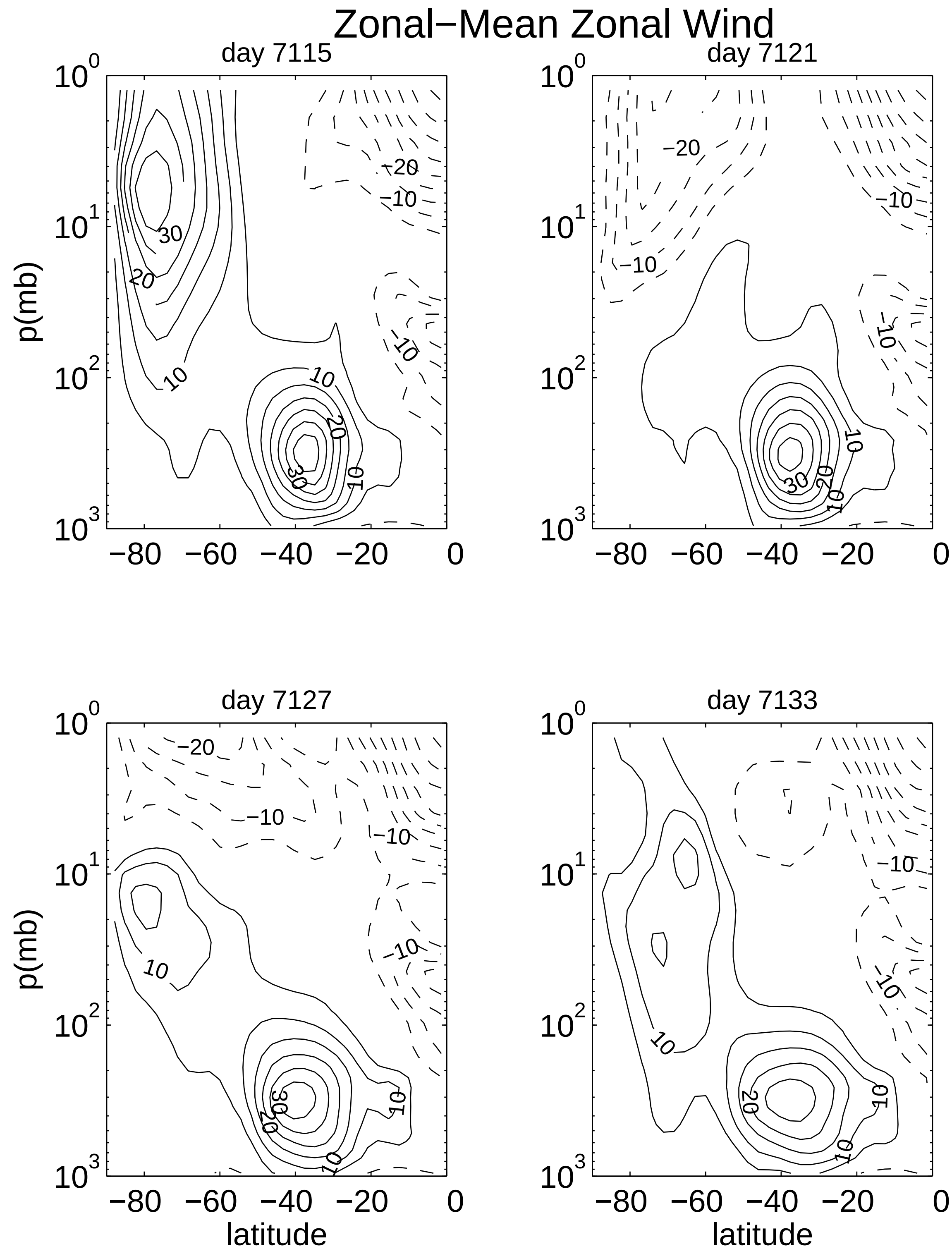

Figure 3: As in Fig. 2, for the zonal wind. The contour interval is $10\,\mathrm{ms}^{-1}$, negative contours are dashed, and the zero contour is omitted.

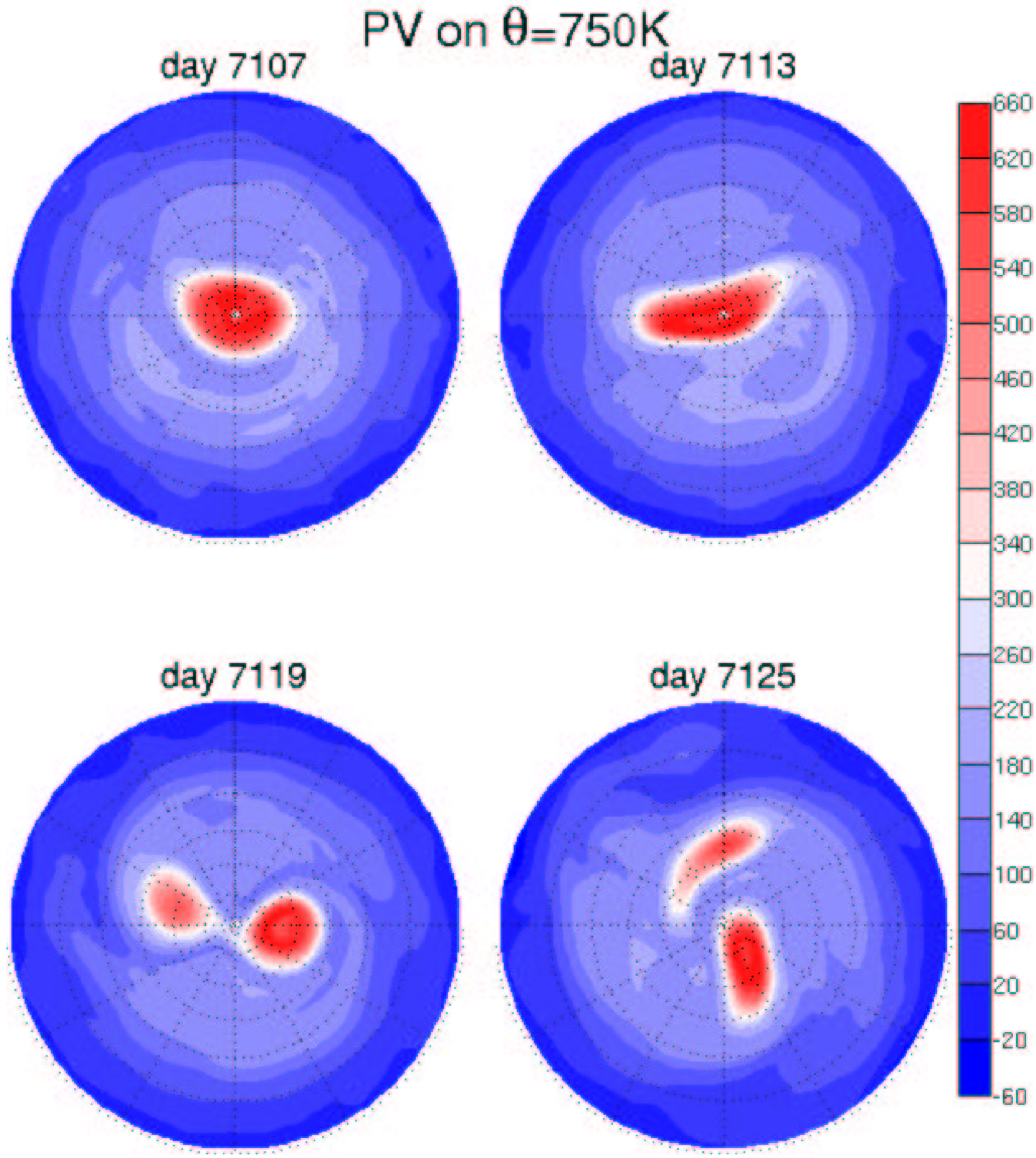

Figure 4: Snapshots of potential vorticity on the 750K isentropic surface around the time of the day-7121 warming. The color shading key is in potential-vorticity units.

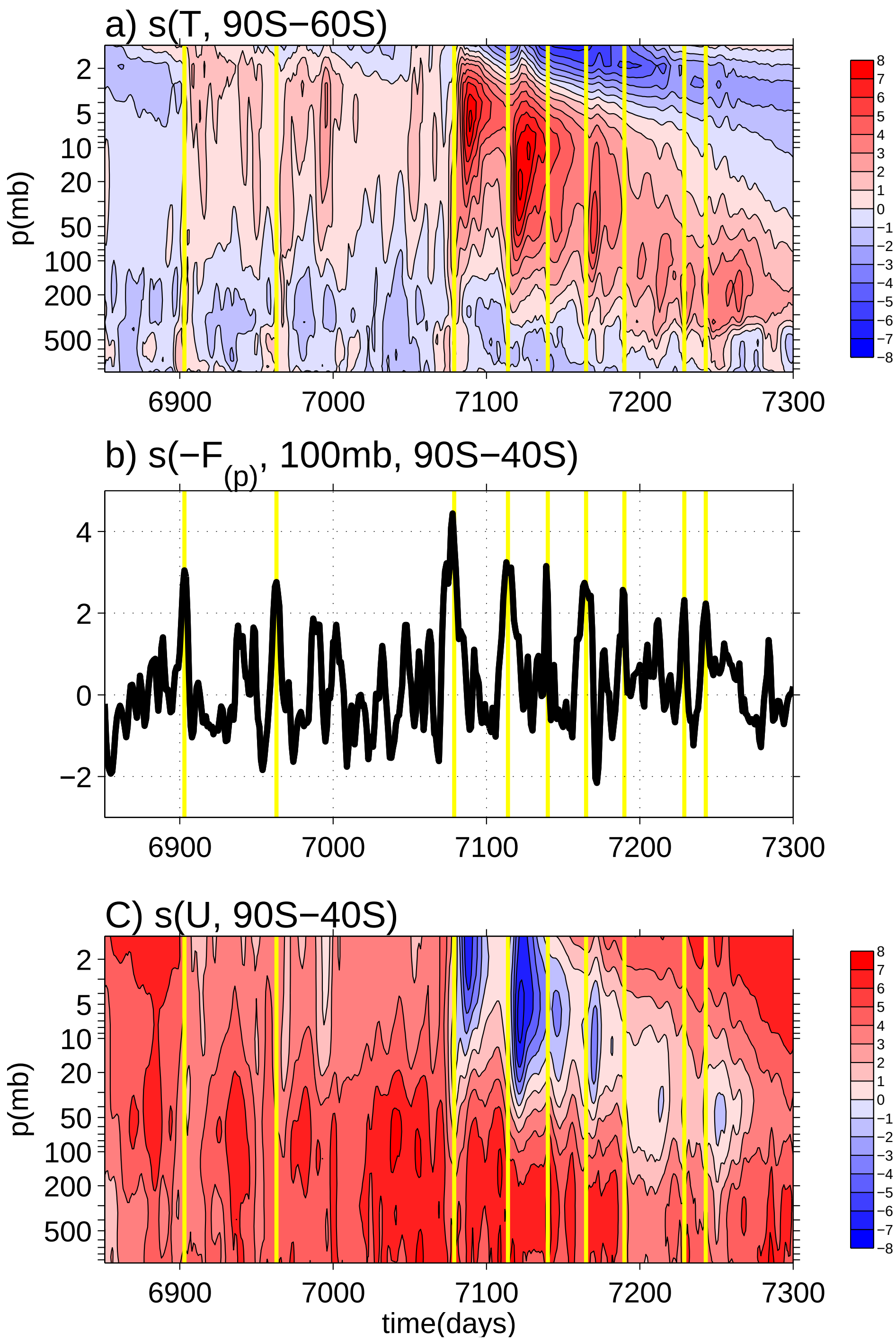

Figure 5: a) 90S-60S meridionally averaged temperature anomaly field, defined as in (1), as a function of pressure and time. Shading interval is one standard deviation. b) 90S-40S meridionally averaged vertical component of the EP flux at 100 mb, in anomaly units as in a). c) As in a), for 90S-40S meridionally averaged zonal-mean zonal-wind. Periods when the vertical EP flux in panel b) are greater than +2 standard deviations are marked with yellow lines in all three panels.

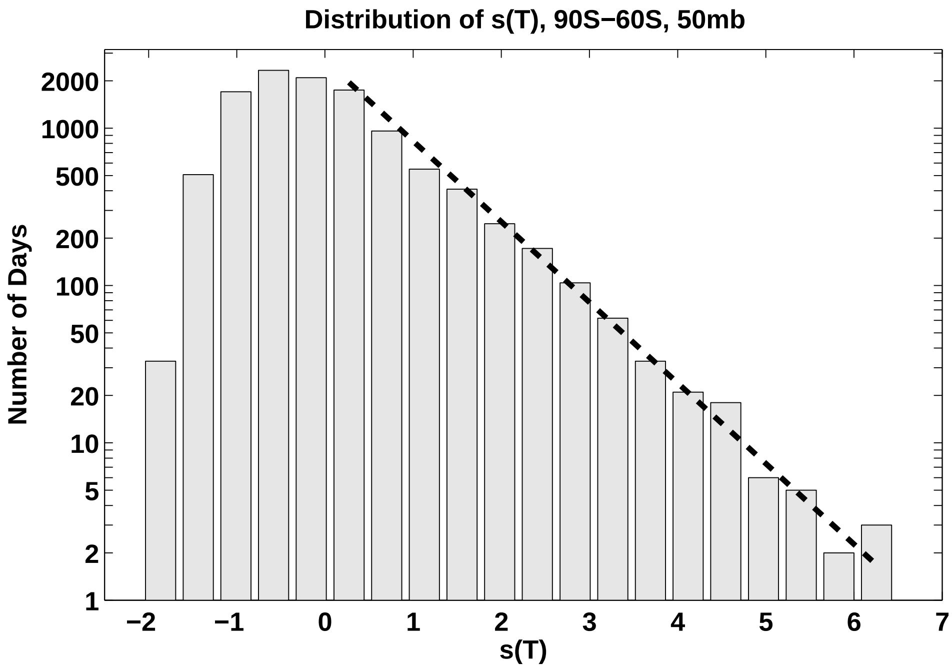

Figure 6: The bars show the number distribution of $s(T)$ in Fig. 1. The dashed line is a fit of the exponential function $10^{-0.51s(T)+3.43}$ to the data for $s(T) > 0$. The constants in this exponential function were obtained by a linear regression; the Pearson r-square coefficient for the fit is 0.68.